INTRODUCTION

The three- and the five-vector P-even T-odd (pseudo-T-noninvariant) correlations of fission products—the so-called TRI-[1,2] and ROT-effect [3]—are now the subject of active investigations and discussions [4, 5]. In the fission process, however, these effects manifest themselves in extremely complicated events. A huge number of possible exit microchannels which differ by the masses of fragments, their spins, relative angular momentum, etc. contribute. Furthermore, the emission of some number of various unregistered light particles attends any fission event and introduces distortions. These and other properties make any correlation of fission fragments with other emitted particles very hard for interpretation. The \((n, \alpha \gamma)\) process looks essentially simpler and nevertheless offers some analogous properties. In particular, one would expect the same P-even T-odd correlations. The idea to consider such a reaction as a process which is reference one for the study of the TRI-effect in fission is realized in the experiment [6]. The \(^{10}\text{B}\) target is used. In the paper [7] a theoretical interpretation of the experimental result obtained in [6]—zero TRI-effect—is presented. The fact that a T-odd effect is not necessarily an actual T-violating one is declared in [7]. It is also declared (before the observation of the ROT-effect) that five-vector and higher-rank T-odd correlations may manifest themselves in this reaction in the case that other targets are used.

In the current paper, these properties of the \((n, \alpha \gamma)\) process are considered in detail. The formalism of the angular correlations in two-step reactions suitable for description of an arbitrary correlation is presented. The selection rules classifying T-odd effects into zero and nonzero ones are discussed. A scheme which may be used to search for actual T-violating effect is demonstrated. Suitable target isotopes are proposed. The reactions \((n, p\gamma)\), \((n, \gamma \alpha)\), and \((p, \alpha \gamma)\) are also considered.

1. FORMALISM OF THE ANGULAR CORRELATIONS

The definitions of angular correlations are formulated in a variety of ways. The vector form serves usually for their notation. As an example, the correlation related to the TRI-effect in the ternary fission is defined by the three-vector form \((\mathbf{k}_{\text{ff}} \cdot [\mathbf{\sigma} \times \mathbf{k}_{\alpha\gamma}])\), where the subscripts \(\text{ff}\) and \(\alpha\) denote the type of emitted particles: the fission fragment and the alpha particle. If the axis of quantization is chosen to be parallel to the vector of polarization \(\mathbf{\sigma}\), the explicit kinematic form of this correlation is the following:

\[
\sum_{m = -1}^{1} \left(1 m 1 - m \right) \frac{4\pi}{3} \text{Re}[Y_{1}^{m}(\theta_{\text{ff}}, \phi_{\text{ff}})Y_{1}^{m}(\theta_{\alpha}, \phi_{\alpha})]. \tag{1}
\]

The correlation associated with the ROT-effect is defined by the five-vector form \((\mathbf{k}_{\text{ff}} \cdot [\mathbf{\sigma} \times \mathbf{k}_{\alpha\gamma}])\). Evidently, it may be written explicitly in the form of the product of five \(Y\) functions of the rank 1 with the proper vector coupling. However, a much more convenient expression appears after the convolutions of the \(Y\) functions depending on one and the same arguments:

\[
\sum_{m = -2}^{2} \left(2 m 2 - m \right) \frac{4\pi}{5} \text{Re}[Y_{2}^{m}(\theta_{\text{ff}}, \phi_{\text{ff}})Y_{2}^{m}(\theta_{\alpha}, \phi_{\alpha})]. \tag{2}
\]

Naturally, the presented formulas do not depend on types of emitted particles and the dynamics of the process. In particular, the kinematics of the correlation \((\mathbf{k}_{\alpha} \cdot [\mathbf{\sigma} \times \mathbf{k}_{\gamma}])\) denoting the ROT-effect in the neutron-induced alpha-gamma cascade is
expressed by formula (2) with the replacements of the subscripts: $ff \rightarrow \alpha$ and $a \rightarrow \gamma$. The current paper is focused on this example of the five-vector correlation; therefore, sizable expressions of the general formalism are presented below, being indexed by these subscripts.

The dynamic form of any correlation must evidently be constituted as a bilinear form of the amplitudes of an investigated process. The overall (i.e., including all possible correlations) and general (i.e., valid for any sequential two-step cascade of an oriented or nonoriented sample) expression can be presented as

$$\begin{align*}
W_{IJL}(\theta_\alpha, \theta_\gamma, \phi_\alpha, \phi_\gamma) &= \sum \rho_0^0(I, I') \varepsilon_{j_\alpha}^m (L_\alpha, L_\gamma') \varepsilon_{j_\gamma}^m (L_\gamma, L_\alpha') \times (L_\alpha, p_{\alpha}, L_\gamma, p_{\gamma}) \varepsilon_{j_\alpha}^{m'} (F) \delta^{2\pi^2} (j_{\alpha} m_{\alpha} j_{\gamma} m_{\gamma} | j 0) \\
& \times \left\{ \begin{array}{c}
J L_\alpha I \\
J L'_\alpha I'
\end{array} \right\}_{J_L} \left\{ \begin{array}{c}
F L_\gamma J \\
F L'_\gamma J'
\end{array} \right\}_{J^*} \delta_{j_{\alpha} j_{\gamma}} \langle J | L_\alpha | I \rangle \ast \langle J | L_\gamma | I \rangle \\
& \times \langle F | L'_\gamma, p_{\gamma} | J \rangle \ast \langle F | L_\gamma, p_{\gamma} | J \rangle.
\end{align*}$$

Here the notation $b = \sqrt{2} b + \mathbb{1}$ is used; $(j_{\alpha} m_{\alpha} j_{\gamma} m_{\gamma} | j 0)$ is the Clebsh–Gordan coefficient, $3 \times 3$ tables are $9j$-symbols; $\rho_0^0(I, I')$ is the statistical tensor of a state in which spins $I$ and $I'$ are mixed; $I$ and $I'$ denote the spins of initial compound nucleus state, $J$ is an intermediate, and $F$ is a final state; $\langle J | L | I \rangle$ is the amplitude of a transition; $L_\alpha, p_{\alpha}, L'_\gamma, p_{\gamma}$ are the angular momenta and parities of the amplitudes determining the multipolarities of the transitions; $\varepsilon_{j_\gamma}^m (lp, l'p')$ is the $m$ component of the efficiency tensor of the rank $j$ which characterizes the capability of a detector to register a product which appears in the transition described by the respective pair of the amplitudes. The sum is over all indices contained in (3) besides $I, J, F$. A particular correlation is defined by the ranks of the statistical tensor $J$ and the efficiency tensors of the detector system $j_{\alpha}, j_{\gamma}$. For more details concerning the expression (3) and the formulas below, see the monograph [8].

The efficiency tensor of an alpha detector $j_\alpha$ can be expressed as

$$\varepsilon_{j_\alpha}^m (l, l') = \frac{1}{\sqrt{4 \pi j_\alpha}} \left( \frac{1}{j_\alpha} \right)^{l + l' - l} \left( \frac{1}{j_\alpha} \right)^{l + l' - l} \langle l 0 l' j_\alpha 0 \rangle Y_{j_\alpha}^m (\theta_\alpha, \phi_\alpha).$$ (4)

The efficiency tensor of the gamma detector insensitive to the polarization takes the form

$$\varepsilon_{j_\gamma}^m (lp, l'p') = \frac{1}{16 \pi} \left( \frac{1}{l} \right)^{l + l' - l} \langle l 1 l' - 1 | j 0 \rangle \times [1 + pp'(-1)^{j'}] S(0) Y_{j_\gamma}^m (\theta_\gamma, \phi_\gamma),$$ (5)

where $S(r)$ is the Stokes parameter. The parameter $S(0)$ signifies the polarization insensitivity. The residual nucleus is not registered; therefore, the tensor of the efficiency of such a "registering" $\varepsilon_{j_\gamma}^m (F)$ should be written as

$$\varepsilon_{j_\gamma}^m (F) = \hat{F}_\gamma \delta_{j_\gamma} \delta_{m m'},$$ (6)

Analysis of the multiresonance problem is a subject of special interest because, as pointed out in [9], overlapping of resonances of different spin may be the origin of $T$-odd correlation. If several resonances contribute significantly to the correlation, then all quantum numbers characterizing the amplitudes should be indexed by the resonances numbers; the sum over these indices appears. The respective resonance amplitudes should be involved in the formalism. Such a cumbersome formalism requires a presentation in a full-size paper. One-resonance case, being a particular one, is adequate to explain selection rules and other qualitative properties of the problem, and to demonstrate the formal scheme. Because of that, we limit ourselves by it in the current paper. In this case, the expression of the statistical tensor produced by the polarized $s$-neutron capture has the form

$$\rho_k^0 (I, I') = \rho_k^0 (I)$$

$$= \frac{1}{4 \pi} Q_{\gamma}^{(s, 0)} \delta_{\gamma, 0} \left\{ \begin{array}{c}
I j I_0 \\
k k 0
\end{array} \right\} \langle I_0 | I \rangle \ast \langle I_0 | I \rangle,$$ (7)

where $Q$ is the degree of the neutron polarization, $s = 1/2$ denotes neutron spin, $J = 1/2$ is the total contributangular momentum, and $k = 1$. The quantum number $I_0$ is the spin of the initial nucleus state, $I$ is the final one.

The discussed correlations are characterized by the tensor ranks: $j_\alpha = 1; j_\gamma = 1; j = 1$ for the TRI-effect and $j_\alpha = 2; j_\gamma = 2; j = 1$ for the ROT-effect, respectively. The $Y$ functions, presented in formulas (1) and (2), are involved in the expression (3) through expressions of the efficiency tensors.

The existence of the Clebsh–Gordan coefficients and the $9j$-symbols in formulas (3)–(7) determines the selection rules for the amplitudes of a certain correlation. Analyzing the TRI-effect, one can find a very expressive example of application of the presented formulas to visualize these rules. Indeed, in the absence of the (parity-conserving or parity-violating) mixing of even and odd amplitudes, the value of efficiency tensor of an alpha detector (4) turns out to be zero because of zero value of the coefficient $\langle 00 | 0 \rangle$. The same is true for a detector of arbitrary heavy particle.